A Simple Method for Parameter Extraction of a PV Module

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Abstract: The aim of this paper is to present a fast and simple method for characterization and modelling of a PV module with due account taken of its application as a teaching tool for undergraduate courses. Thus, the paper presents a simplified mathematical analysis that underpins the modelling process of a PV module, which is based on the single-diode model (SDM). Subsequently, the paper explains a fast and straightforward method for extracting the parameters of the single-diode model from experimentally obtained I-V (current-voltage) characteristic of a PV module. The parameter extraction strategy uses a spreadsheet approach to solve the nonlinear equations of the model, which alleviates the need for any nonlinear equation solvers. The method was used, as a laboratory exercise for engineering students, to extract the parameters of a small monocrystalline silicon PV module and the results concurred well with the manufacturer's datasheet and with experimental results. The differences were within the manufacturer's specified tolerance of 10%.

Keywords: *Ideality factor, parallel resistance, parameter extraction, photon current, photovoltaic systems, saturation current, series resistance.*

1. INTRODUCTION

When integrating photovoltaic systems into the undergraduate teaching of renewable energy technologies, it is necessary that students have a good understanding of the modelling and characterization process of a PV generator. However, this can be a complex process and requires a sound understanding of numerical and/or analytical methods of solving systems of nonlinear equations. Therefore, the aim of this paper is to present a concise mathematical formulation of the single-diode model equations of a PV module and demonstrates a fast and simple method of solving these equations.

The design, analysis, and simulation of a PV system requires a lumped circuit parameter model of the PV generator. A PV generator could be as simple as a single PV cell, a PV module consisting of several cells connected in series, or more typically an array of several modules arranged in series-parallel combinations to deliver the rated power at the required terminal current and voltage levels. For this purpose, the single-diode model has been commonly used to model a PV generator due to its simplicity and accuracy [1]. The SDM for a PV generator is shown in Figure 1 and the terminal I-V and P-V (power-voltage) characteristics of a typical PV generator are shown in Figure 2. The P-V curve exhibits a maximum power point (MPP) where a PV generator must be operated for maximum efficiency. However, the I-V characteristic and hence the location of the MPP changes with variations in irradiance and temperature [2]. Therefore, the power processing system in a PV plant normally includes a maximum power point tracker (MPPT). The problem of tracking the MPP is compounded due to partial shading (PS), which can have adverse effects on the performance of a PV system [3]. Mitigation of the effects of PS involves the use of bypass diodes, which can lead to multiple peaks in the P-V curve [4], [5]. Therefore, the design and simulation of MPPTs, exploring the effects of partial shading, and the need to efficiently size a PV generator require an equivalent circuit model of the PV generator.

Numerous analytical [6] and numerical [7] schemes to derive such an equivalent circuit have been reported in the literature with varying degrees of complexity and accuracy [8]. In this paper, a simple method for extracting the five parameters of the SDM model, namely the photocurrent, the series and parallel resistances, the saturation current, and the ideality factor is demonstrated.

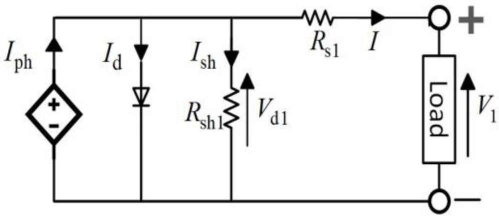

Figure 1. The single-diode equivalent circuit model of a PV cell.

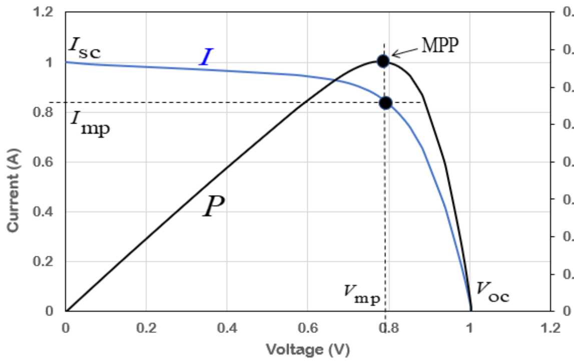

Figure. 2 Normalised I-V and P-V curves of a typical PV module.

The method uses several proven simplifications and approximations and three nonlinear equations, which are consequently solved iteratively using a spreadsheet as explained in section 3. The simplicity of the method makes it attractive as a teaching tool and a laboratory exercise for electrical engineering students. Following this introduction, the mathematical background for extracting the parameters of the single-diode model is presented in section 2. The method is explained with the aid of an example for extracting the single-diode model parameters of a small PV module in section 3. Finally, section 4 presents the conclusions of the work.

2. MATHEMATICAL ANALYSIS

The SDM of a single PV cell, shown in Figure 1, consists of an insolation-controlled current source I_{ph}, a diode, and the resistances R_{s1} and R_{sh1} which represent the series and shunt parasitic resistances of the cell respectively. The terminal current, is given by

$$I = I_{ph} - I_d - I_{sh} \tag{1}$$

where I_d , is the diode current and I_{sh} is the shunt resistance current. The diode current I_d is given in terms of the diode voltage V_{d1}, the reverse saturation current I_o and the ideality factor a of the diode, by the Shockley equation as

$$I_d = I_o[\exp(V_{d1}/aV_t)-1] \tag{2}$$

where V_t (V) is the thermal voltage which is defined in terms of the temperature T in Kelvin (k), the electronic charge $q=1.602\times10^{-19}$ (C) and the Boltzmann's constant $k = 1.380\times10^{-23}$ (J/k) as

$$V_t = kT/q \tag{3}$$

Note that the subscript 1 indicates a single cell. The current in the parallel resistance I_{sh} is given by

$$I_{sh} = V_{d1}/R_{sh1} \tag{4}$$

The diode voltage may be expressed as

$$V_{d1} = V_1 + IR_{s1} \tag{5}$$

Therefore, the terminal current I and voltage V_1 of the SDM of a single cell are related by the implicit nonlinear and transcendental equation

$$I = I_{ph} - I_o[\exp(\frac{(V_1+IR_{s1})}{aV_t})-1] - \frac{(V_1+IR_{s1})}{R_{sh1}} \tag{6}$$

The single-diode model can be easily adjusted to model a PV module consisting of N_s identical cells connected in series as shown in Figure 3 [9]. The terminal current I, the photocurrent I_{ph} and the diode current I_d of the module are the same as those for any single cell within the module. The diode voltage of a single cell is given in terms of the module current *I*, and voltage *V*, as $V_{d1} = V / N_s + IR_{s1}$ which may be written as

$$V_{d1} = (V + IN_s R_{s1}) / N_s \tag{7}$$

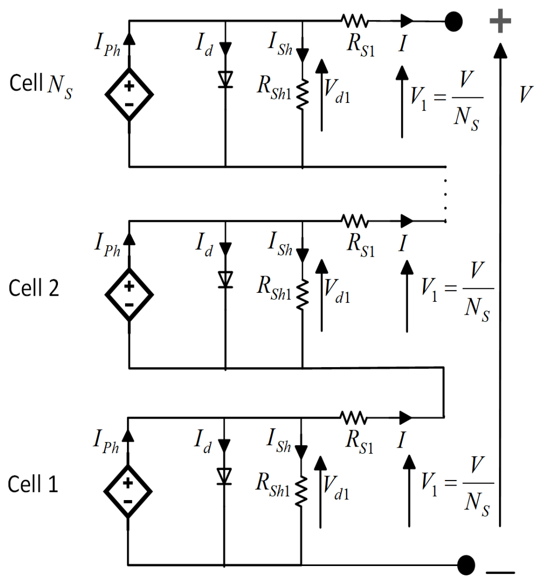

Figure 3. The single-diode model of a PV panel consisting of N_s series-connected cells.

Therefore, the terminal module current, which is the same as the single-cell current, may now be written as

$$I = I_{ph} - I_o[\exp(\frac{V+IN_s R_{s1}}{N_s a V_T}) - 1] - \frac{V+IN_s R_{s1}}{N_s R_{sh1}} \tag{8}$$

However, the total series resistance of the module, which is typically less than $1\,\Omega$, is

$$R_s = N_s R_{s1} \tag{9}$$

Similarly, the total shunt resistance of the module, which is typically in the order of few hundred ohms, is

$$R_{sh} = N_s R_{sh1} \tag{10}$$

Therefore, the terminal current and voltage of the module are related by

$$I = I_{ph} - I_o[\exp(\frac{V+IR_s}{N_s a V_t}) - 1] - \frac{(V+IR_s)}{R_{sh}} \tag{11}$$

To model a PV panel, the five parameters R_s, R_{sh}, a, I_o, and I_{ph} must be determined. These parameters are not included in manufacturers' datasheets of PV modules. However, they can be extracted from information normally provided in the datasheet of a PV module. A typical datasheet includes the I-V data at three vital points: the short-circuit point $(0, I_{sc})$, the open-circuit point $(V_{oc}, 0)$, and the maximum power point (V_{mp}, I_{mp}). Some datasheets also include the full I-V characteristic. However, the data provided by a datasheet is always specified at only one operating condition, namely the standard test condition (STC). (STC: insolation $G = 1000\,\text{W/m}^2$, Air Mass=1.5, $T = 25^o\text{C}$). Therefore, parameters extracted from STC data are only valid at STC and hence, for any other operating condition of temperature and insolation, these parameters must be adjusted accordingly [2].

Extraction of the Photocurrent

This parameter can be estimated from the SC point by substituting $V = 0$ and $I = I_{sc}$ in Eq. (11)

$$I_{sc} = I_{ph} - I_o[\exp(\frac{I_{sc} R_s}{N_s a V_t}) - 1] - \frac{I_{sc} R_s}{R_{sh}} \tag{12}$$

Since the series resistance is very small, typically less than 1, the diode voltage $I_{sc} R_s$ is also very small and comparable to the thermal voltage, that is $\exp(I_{sc} R_s / N_s a V_t) \approx 1$. Therefore, the diode and shunt resistance currents are too small compared to the short-circuit current and hence, they can be neglected [10] [11]. Consequently Eq. (11) reduces to $I_{ph}=I_{sc}$. To estimate the photocurrent at any other condition of temperature T (k) and insolation $G\,(\mathrm{W/m^2})$, the following expression may be used [12]

$$I_{ph}=\left[I_{sc,STC}+\alpha_{I,STC}(T-T_{STC})\right]\frac{G}{G_{STC}} \tag{13}$$

where $I_{sc,STC}$ is the short-circuit current at STC and $\alpha_{I,STC}$ is the temperature coefficient of the short-circuit current at STC, which are always available in the datasheet.

Extraction of the Shunt Resistance

The effect of the shunt resistance is dominant at higher currents, i.e. near the short-circuit point. Therefore, the derivative of the I-V curve at the short-circuit point may be used to estimate the shunt resistance. The derivative of Eq. (11) at any point along the I-V curve can be readily derived as

$$\frac{dI}{dV}=-\frac{I_o}{aN_sV_T}\left[\exp\left(\frac{(V+IR_s)}{aN_sV_t}\right)\left(1+R_s\frac{dI}{dV}\right)\right]-\frac{1}{R_{sh}}-\frac{R_s}{R_{sh}}\frac{dI}{dV} \tag{14}$$

Solving for the derivative

$$\frac{dI}{dV}=-\left[\frac{I_o}{aN_sV_t}\exp\left(\frac{(V+IR_s)}{aN_sV_t}\right)+\frac{1}{R_{sh}}\right]\Big/\left[1+\frac{R_s}{R_{sh}}+\frac{I_oR_s}{aN_sV_t}\exp\left(\frac{(V+IR_s)}{aN_sV_t}\right)\right] \tag{15}$$

At the short-circuit point, the derivative becomes

$$\left.\frac{dI}{dV}\right|_{sc}=-\left[\frac{I_o}{aN_sV_t}\exp\left(\frac{I_{sc}R_s}{aN_sV_t}\right)+\frac{1}{R_{sh}}\right]/\left[1+\frac{R_s}{R_{sh}}+\frac{I_oR_s}{aN_sV_t}\exp\left(\frac{I_{sc}R_s}{aN_sV_t}\right)\right] \tag{16}$$

The term $I_o\exp(I_{sc}R_s/aN_sV_t)$ represents the diode current and this is too small compared to the short-circuit current and thus it can be neglected [10] [11]. In addition, since $R_s \ll R_{sh}$, the term R_s/R_{sh} may also be neglected [13]. Therefore, the derivative can be approximated as

$$\left.\frac{dI}{dV}\right|_{sc}=-1/R_{sh} \tag{17}$$

Hence, the shunt resistance can be estimated from the slope of the I-V curve at the short-circuit point.

Extraction of the Series Resistance

The effect of the series resistance is significant at higher voltages and low currents. Therefore, the value of the series resistance may be estimated from the slope of the I-V curve at the open-circuit point. Substituting the OC point $(V_{oc},0)$ in the general expression for the derivative in (15)

$$\left.\frac{dI}{dV}\right|_{OC}=\left[-\frac{I_o}{aN_sV_t}\exp\left(\frac{V_{oc}}{aN_sV_t}\right)-\frac{1}{R_{sh}}\right]\Big/\left[1+\frac{R_s}{R_{sh}}+\frac{I_oR_s}{aN_sV_t}\exp\left(\frac{V_{oc}}{aN_sV_t}\right)\right] \tag{18}$$

The term $I_o\exp(V_{oc}/aN_sV_t)$ represents the diode current and since under open-circuit condition, the output current is zero, the diode current is the same as the photon current (less the negligibly small current in the shunt resistance) and the photon current is the same as the short-circuit current, i.e.

$$I_o\exp\left(\frac{V_{OC}}{aN_sV_T}\right)=I_{sc} \tag{19}$$

Hence the diode current is the same as the short-circuit current. The derivative becomes

$$\left.\frac{dI}{dV}\right|_{OC}=-\left(\frac{I_{sc}}{aN_sVt}+\frac{1}{R_{sh}}\right)\Big/\left(1+\frac{R_s}{R_{sh}}+\frac{I_{sc}R_s}{aN_sV_t}\right) \tag{20}$$

In practice, $1/R_{sh} \ll I_{sc}/aN_sV_T$ and hence, this term and the term R_s/R_{sh} may be neglected. The series resistance may, therefore, be estimated from

$$R_s = -\left.\frac{dV}{dI}\right|_{oc} - \frac{aN_sV_t}{I_{sc}} \tag{21}$$

The first term can be estimated from I-V curve. However, the ideality factor in the second term is unknown and must be determined.

Extraction of the Reverse Saturation Current

The reverse saturation current may be estimated at the open-circuit point where its effects are most significant. At this point, the output current $I = 0$ and $I_{ph} = I_{sc}$. Substituting in Eq. (11) and using the approximation $\exp(V_{oc}/aN_sV_T >> 1)$, the saturation current may be estimated from

$$I_o = (I_{sc} - \frac{V_{oc}}{R_{sh}})\exp(\frac{-V_{oc}}{aN_sV_t}) \tag{22}$$

The open-circuit voltage V_{oc} and N_s can be obtained from the datasheet. However, the ideality factor a is unknown needs to be determined.

Extraction of the Ideality Factor

Substituting the MPP point in the general equation of the module current, i.e. in Eq. (11)

$$I_{mp} = I_{sc} - I_o[\exp(\frac{(V_{mp} + I_{mp}R_s)}{aN_sV_t}) - 1] - \frac{(V_{mp} + I_{mp}R_s)}{R_{sh}} \tag{23}$$

To determine the parameters I_o, R_s, and a, the three Eqs. (21), (22) and (23) may be solved simultaneously using a nonlinear equation solver, such as MATLAB. However, numerical solutions can be very sensitive to the initial guess and conversion can be problematic depending on the initial guess amongst other factors [14]. An easier approach, is to use a spreadsheet solution as explained in the next section.

3. EXPERIMENTAL SETUP AND RESULTS

The experiment uses readily available apparatus consisting of a variable 400 W light source that simulates the spectrum of the sunlight, a solar insolation meter, a cooling fan, a thermometer, and a variable resistance used as a load. The 1 W Parallax 750-00030 monocrystalline silicon solar panel whose specifications are: $N_s = 12$, $V_{oc} = 6.9\,\text{V}$, $I_{sc} = 0.18\,\text{A}$, $V_{mp} = 6\,\text{V}$, and $V_{mp} = 6\,\text{V}$ was used to illustrate the parameter extraction method. The datasheet did not include the I-V curve; therefore, this was obtained in the laboratory. The variable light source was adjusted until the measured insolation at the surface of the panel was 1000 (W.m^{-2}). The fan helped maintaining the surface temperature around $25\,^oC$ to approximate a STC operating conditions. Using the variable resistance, the terminal voltage across the PV panel was swept from zero to V_{oc}. The resulting I-V curve and the corresponding P-V curve are shown in Figure 4. These were used in extracting the parameters of the single-diode model as illustrated in the next subsections.

Extraction of the Photocurrent and the Shunt Resistance

The photon current is the same as the short-circuit current. This was obtained from the datasheet and confirmed by experiment as $I_{ph} = 0.18\,\text{A}$ The shunt resistance was estimated from the slope of the I-V curve at the short circuit condition.

$$\left.\frac{dI}{dV}\right|_{sc} = -\frac{1}{R_{sh}} \rightarrow R_{sh} = 385\,\Omega \tag{24}$$

Extraction of the Ideality Factor, Series Resistance and Saturation Current

Using a Microsoft Excel spreadsheet these parameters were obtained as follows: The ideality factor a was swept from 1 to 2 in steps of 0.1 and each step the saturation current I_o was calculated using (22) and thus, the series resistance calculated using Eq. (21) as illustrated in the spreadsheet in Table 1. Then, for each set of values of a , I_o , and R_s , an I-V curve for the module was derived as follows: Using another spreadsheet, the diode voltage V_{d1} was swept from 0 to 0.6 V in steps of 0.05 V and at each step the diode current and the shunt resistance current were calculated using

$$I_d = I_o(e^{qV_{d1}/akT} - 1) \tag{25}$$

And

$$I_{sh} = V_{d1}/(R_{sh}/N_s) \tag{26}$$

The module current was consequently obtained from

$$I = I_{sc} - I_d - I_{sh} \tag{27}$$

The module voltage was calculated using

$$V = N_s\,[V_{d1} - I(R_s/N_s)] \tag{28}$$

Table 1. Sweeping the value of the ideality factor and calculating the values of I_o and R_s.

a	aN_sV_t (V)	I_o (A)	R_s (Ω)
1	0.308045	3.0326E-11	1.788639
1.1	0.338849	2.3237E-10	1.617503
1.2	0.369654	1.2681E-09	1.446367
1.3	0.400458	5.3299E-09	1.275231
1.4	0.431263	1.8248E-08	1.104095
1.5	0.462067	5.3022E-08	0.932959
1.6	**0.492872**	**1.3483E-07**	**0.761823**
1.7	0.523676	3.0720E-07	0.590687
1.8	0.554481	6.3875E-07	0.419551
1.9	0.585285	1.2296E-06	0.248414
2	0.616090	2.2170E-06	0.077278

Finally, the set of values of a , I_o , and R_s that resulted in the closest match between the estimated I-V curve and the datasheet/experimental data, was chosen. This is illustrated in Table 2 for the case of a=1.6, i.e. when $I_o = 1.3483 \times 10^{-7}$ A and $R_s = 0.761823\,\Omega$. This was the set that resulted in the best match as illustrated in Figure 5, which shows a comparison between the laboratory measured I-V characteristic and the estimated characteristics using the extracted parameters of the PV module when the ideality factor is a=1.6.

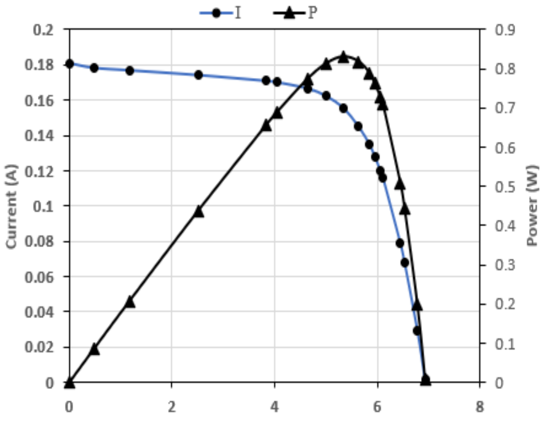

Figure 4. Measured I-V and P-V curves at 1000 W/m^2.

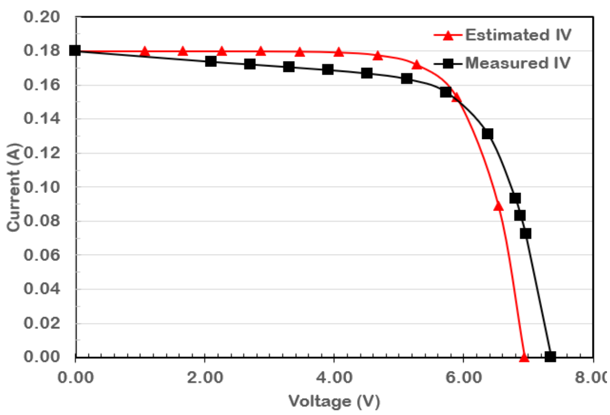

Figure 5. The measured and extracted I-V curves.

4. CONCLUSION

The paper presented the mathematical analysis and a fast and simple method for extracting the parameters of the single-diode model of a PV module form the experimentally obtained I-V curve. The simplicity of the method lends itself as a useful tool for introducing PV module characterisation and parameters extraction to engineering and science students who may not be conversant with numerical methods. Results obtained were within 10% of the experimental and manufacturer's specified data. For example, the estimated MPP was (5.7 V, 0.16 A) compared to the manufacturer's point of (6 V, 0.17 A), and the estimated open-circuit voltage was 7.3 V compared to the manufacturer's value of 6.9 V.

Table 2. Sweeping the diode voltage and calculating the module current and voltage.

V_d (V)	I_d (A)	I_{sh} (A)	I (A)	V (V)	P (W)
0.0	0.0	0.0	0.18	0.0	0.0
0.1	1.404E-06	4.376E-08	0.1800	1.0629	0.1913
0.15	5.063E-06	1.578E-07	0.1800	1.6629	0.2993
0.2	1.743E-05	5.431E-07	0.1800	2.2629	0.4073
0.25	5.919E-05	1.845E-06	0.1799	2.8629	0.5152
0.3	2.003E-04	6.242E-06	0.1798	3.4630	0.6226
0.35	6.769E-04	2.110E-05	0.1793	4.0634	0.7286
0.4	2.287E-03	7.129E-05	0.1776	4.6647	0.8286
0.45	7.727E-03	2.408E-04	0.1720	5.2689	0.9064
0.5	2.610E-02	8.136E-04	0.1531	5.8834	0.9006
0.55	8.818E-02	2.749E-03	0.0891	6.5321	0.5818
0.58	1.744E-01	5.435E-03	0.0002	6.9358	0.0014

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